The application of the infrared thermography on titanium alloy for studying fatigue behavior

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ABSTRACT. The infrared thermography is an attractive tool for studying the fatigue behavior of materials. Based on two theoretical models of fatigue damage indicators, this work studied the fatigue properties of the virgin Ti-6Al-4V alloy. According to the two damage indicators and the energy theory, the relationship between the macro-phenomenon and the micro-structural evolution during fatigue process was discussed. The fatigue limit of the titanium alloy was rapidly determined based on the measured temperature increment signals. The capability of the infrared thermographic method on the evaluation of fatigue properties was validated.

KEYWORDS. Thermography; Fatigue indicator; Ti-6Al-4V alloy; Fatigue limit.

INTRODUCTION

In practical applications, fatigue failure occurs everywhere including automobiles, airplanes, and vessels, etc. This often leads to disastrous damage to human beings. As a consequence, fatigue properties of materials should be well known before mechanical designs. However, it is difficult to obtain the fatigue properties of materials due to the time-consuming and expensive costing of the traditional fatigue tests.

During the fatigue evolution process, most of the plastic work dissipates into the surroundings as heat energy, and simultaneously generates a heterogeneous temperature field on the surface of materials and components. The measurement of the thermal signals makes it possible to visibly detect the appearance of fatigue damage and to predict the fatigue parameters of materials. There are many measuring methods used to monitor the temperature field evolution [1]. However, the infrared thermography is more promising due to the high accuracy and rapid response of the infrared camera [2, 3]. Over the last 30 years, the infrared thermography, as a non-destructive, full-field and non-contact measuring method, has been widely and successfully used to study the fatigue behavior of materials and components [4-7].

The infrared thermographic method was first proposed by G. Curti et al. [5] by using the surface temperature increment signals as the major fatigue indicator. And also some efficient methods based on the infrared thermographic analysis have been developed to correlate the temperature signal evolution with the corresponding fatigue parameter. Luong et al. [4] proposed to use the dissipated thermal energy under a given number of cycles to get the fatigue limit. La Rosa et al. [8] analyzed the temperature signals of the external surface during the application of cyclic loading to evaluate the dynamic behavior of an element and to determine the fatigue limit. Kim and Jeong [9] found a linear correlation between the temperature increment squared and the logarithm of the fatigue life. Similarly, a modified thermographic method using the iterative algorithm was presented and confirmed by Curà et al. [10], and the method could give more accurate prediction of the fatigue limit. Meneghetti [11] defined a theoretical model in order to derive the specific heat loss per cycle from the temperature measurements during fatigue tests, and the fatigue strength of smooth and notched specimens was analyzed by this model.

Fatigue failure will occur once the accumulated energy due to the micro-plastic deformation reaches a constant threshold value. Based on this physical hypothesis, Fargione et al. [6] confirmed the connection between the fatigue limit and the quantity of heat dissipation by testing a given element to failure. The development of the energetic method facilitates the application of this infrared thermography in predicting the fatigue behavior of materials. Pastor et al. [12] and Fan et al. [13,14] associated the infrared thermographic method with the intrinsic dissipation and accumulated energy to investigate metallic fatigue behavior, including fatigue limits, S/N endurance curves, and to identify the initiation of a fatigue crack and its location. In addition, Ummenhofer and Medgenberg [15] investigated the fatigue damage by a specialized data processing method and developed the infrared thermographic method. Risitano et al. [16-18] investigated the cumulate fatigue damage by infrared thermographic method. The results demonstrated accordance with the traditional test rather well.

The purpose of the present work is to rapidly study the fatigue behavior of Ti-6Al-4V alloy by using different fatigue damage indicators provided by the infrared thermography. At the same time, the fatigue crack initiation and propagation were observed, and the relationship between the internal microstructures and mechanical properties was discussed by analyzing the evolution of the fatigue damage indicators.

THEORETICAL MODELS

Relative temperature increment

Fatigue damage is known as energy dissipation process accompanied by the temperature signal variation. The temperature signals linked with the energy dissipation enable us to understand the energy transformation, toughness reduction and damping vibration of materials. Therefore, the fatigue process can be qualitatively evaluated by using the relative temperature increment signals.

During fatigue tests, to avoid any possible errors induced by the environmental perturbation and the experimental system sensitivity, the relative temperature increment ΔT on the hot-spot zone of the specimen surface is used to describe the fatigue damage status:

$$\Delta T = T_{\mathrm{m}} - T_0 \qquad (1)$$

where T_{m} is the maximum temperature signal on the zone, and T_0 is the initial temperature signal.

Standard deviation of stress

Micro-cracks often initiate from local points due to the stress concentration effect in the micro-size. The fatigue damage distribution is not uniform when a material is subjected to cyclic/random loadings. The distribution of the local stress levels can be described by the standard deviation. The stress state on the hot-spot zone, due to the localized high stress, enables us to qualitatively identify the critical location responsible for the final fracture. Accordingly, the economic losses caused by the sudden fatigue fracture might be greatly decreased by analyzing this damage indicator.

The stress level used here is the thermoelastic stress calculated by the equation below:

$$\Delta T = -\frac{a}{\rho C_{\mathrm{p}}} \cdot T \cdot \Delta\sigma \qquad (2)$$

where

a is the coefficient of linear expansion;

C_{p} is the specific heat capacity;

ϱ is the material density;

T is the absolute temperature;

$\Delta\sigma$ is the change of the sum of principal stresses;

ΔT is the change of temperature.

The stress pattern can be visibly obtained using the infrared camera, and each pixel stands for a point in the selected zone Ω. Thus, the standard deviation of the stress can be written as:

$$\sigma_{\mathrm{SDS}} = \sqrt{\frac{1}{N} \sum_{x,y\in\Omega} (\sigma(x,y) - \sigma_{\mathrm{m}})^2} \qquad (3)$$

where
σ_m denotes the average stress in the zone Ω;
$\sigma(x, y)$ denotes the stress value at the point (x, y);
N denotes all the points in the zone Ω.

EXPERIMENT

Material and specimen

The material used in the present research is Ti-6Al-4V alloy. The chemical composition of this alloy (in wt.%) is given in Tab. 1 [19]. Fig.1 shows the dimension of the tested specimens. The tested specimens were made from a sheet of titanium alloy.

Ti	Al	V	Fe	O	N	H
Bal.	6.27-6.32	4.15-4.19	0.18-0.20	0.18-0.19	0.012-0.014	0.0041

Table 1: Chemical composition of Ti-6Al-4V alloy (wt.%).

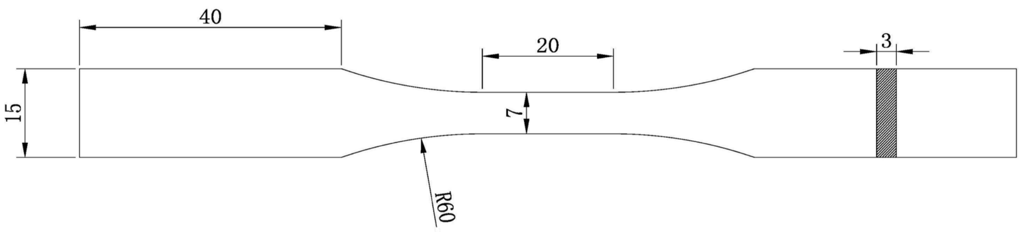

Figure 1: Size of the specimen (unit: mm).

Experimental procedures

Fatigue tests were carried out at room temperature without disturbance of the external heat resource. The testing system is composed of MTS810 system, infrared thermographic system, lock-in module, and controlling computers [2, 3].
Before fatigue tests, all the specimens were polished with fine grit papers, and then painted the specimens black to improve the heat radiation and reduce the heat reflection. The stress ratio was set as $R=\sigma_{min}/\sigma_{max}=-1.0$ with a low frequency of f=20Hz. The successive stepwise loading procedure was applied to the same specimen [2]. To minimize fatigue damage accumulation, the cyclic stress was applied from 300MPa with steps of 50MPa until the final fracture. The thermal images on the hot-spot zone were recorded simultaneously by the infrared camera to perform the subsequent data analysis, as shown in Fig.2.

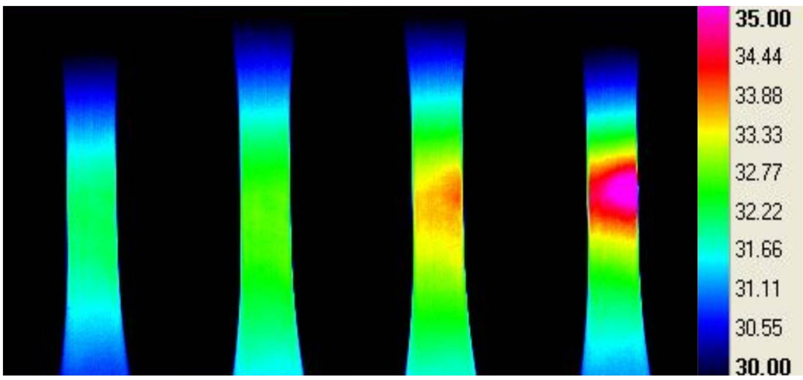

Figure 2: Hot-spot zone evolution.

RESULTS AND DISCUSSION

Qualitative identification of the fatigue damage

Temperature evolution is mainly attributed to the thermo-elastic effect, inelastic effect and heat conduction effect. The fluctuating temperature signals are attributed to the thermo-elastic effect. The cyclic temperature amplitude increases with the increasing cyclic loading amplitude. However, the thermo-elastic effect has no contribution to the average temperature increment [20]. Fig.3 presents the relative temperature evolution at different stress levels.

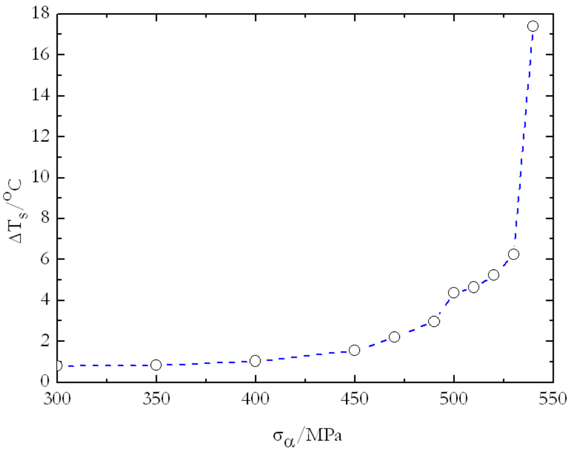

Figure 3: Temperature increment at different stress amplitude.

The elastic stress controls the mechanical responses of the tested specimens when the stress level is lower than the fatigue limit of Ti-6Al-4V alloy. During this period, the specimen mainly takes place elastic deformation, and the temperature signal variation is mainly induced by the non-plastic effects, i.e. viscosity effect etc. If the stress level is higher than the fatigue limit, micro-cracks would initiate from the specimen boundaries, such as the corner and the free surface. The fatigue cracks initiated along the axial direction of 45^o, and then coalesced to form a main macro-crack. The main crack propagated perpendicular to the principal stress direction. The plastic strain energy continues to accumulate during the fatigue evolution process. Most of the mechanical energy was dissipated as heat energy heating up the specimen.

Fig.4 shows variations of the stress standard deviation of the material. There is no obvious plastic deformation when the applied stress is lower. However, if the stress is higher than the fatigue limit, it sets to increase sharply in the localized zone due to the stress concentration effect. The break point indicates that the mechanisms related to fatigue failure have changed into plastic effect. Local stress concentration, due to pores and impurities, governs the stress distribution. The damage status can be qualitatively identified by the standard deviation to avoid the sudden fracture. From Fig.4, the standard deviation of the Ti-6Al-4V alloy is small when the fatigue stress amplitude is lower than the fatigue limit. However, the standard deviation of the Ti-6Al-4V continues increasing with the increasing stress.

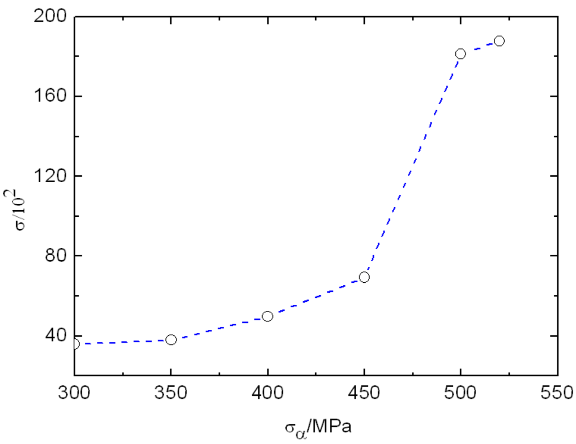

Figure 4: Standard deviation of stress at different stress amplitude.

Fatigue limit prediction

In [21], the interpolated fatigue limit of Ti-6Al-4V alloy at 10^6 cycles was reported as 451 MPa. This value would be used to compare with the infrared thermographic results, and then the errors between the predicted parameter σ_p and the traditional parameters σ_f would be presented in following section.

The temperature increment signals on the hot-spot zone were considered as a fatigue damage indicator for the fatigue behavior analysis. The asymptotic temperature increments were used to determine the fatigue limit stress. Based on the couples of (ΔT_s, σ_a^2), a good linear correlation was plotted between the applied stress range squared and the asymptotic temperature increment in Fig.5. The fatigue limit σ_p was determined as 423 MPa by extrapolating the straight line down to zero at the abscissa axis.

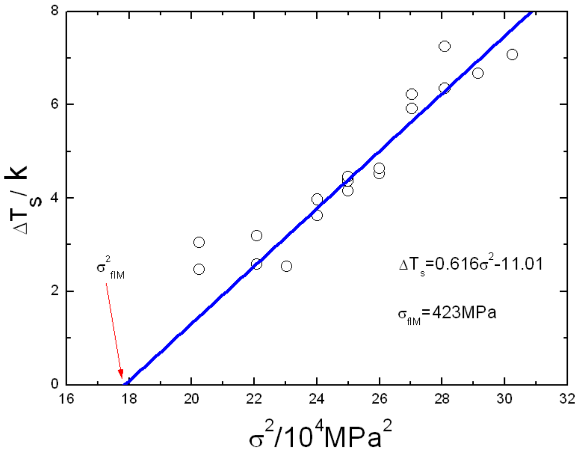

Figure 5: Fatigue limit stress by the infrared thermographic method.

Discussion

The error of the fatigue limit σ_f by traditional method and predicted fatigue limit σ_p were obtained by the following formula, presented in Tab. 2:

$$\delta\% = \left|\frac{\sigma_f - \sigma_p}{\sigma_f}\right| \times 100 \tag{5}$$

The difference between these two results is 6.21%. The low value of error δ% demonstrates that the thermographic method is applicable for the evaluation of the fatigue limit in practical engineering.

Method	σ_f (MPa)	error
Traditional	451	/
Thermography	423	6.21%

Table 2: Comparison.

The above fatigue tests can be divided into three phases. At lower stress stage, which is that the temperature increases slowly, and the intrinsic dissipation is practically null. The internal microstructure evolution is reversible under the elastic stress. However, when the stress is close to the fatigue limit, the local stress may be beyond the yield limit due to the stress concentration in micro-scale. Consequently, the slip band begins to form, and numerous micro-cracks initiate here. Fatigue damage sets to accumulate continuously. If the stress is higher than the fatigue limit stress, all the above damage indicators will increase drastically.

Conclusions

(1) The infrared thermographic method enables us to qualitatively and quantitatively evaluate the fatigue behavior of titanium alloy.

(2) All the fatigue damage indicators can describe the fatigue damage evolution process. The macro-phenomenon and internal microstructure evolution are associated by the energy theory.
(3) The low error between the predicted fatigue limit and the traditional value demonstrates the reliability of the infrared thermographic method in predicting fatigue parameters of materials and components.
(4) It is a fast and accurate technique for fatigue evaluation using various damage indicators resorting to the infrared technique. Consequently, the method may be used to identify fatigue damage status of structures in service in the future work.

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NOMENCLATURE

R	stress ratio
ϱ	material density
C_p	specific heat capacity
a	coefficient of linear expansion
k	heat conduction coefficient
ψ	Helmholtz free energy
ε	strain tensor
a	internal variables
γ^e	external heat resource
d	intrinsic dissipation
σ_α	stress amplitude
σ_m	average stress
$\sigma(x, y)$	stress value at the point (x, y)
σ_{SDS}	standard deviation of stress
σ_p	predicted fatigue limit stress
σ_f	fatigue limit stress
ΔT	temperature increment
T_0	initial temperature
T_m	average temperature
ΔT_s	stationary temperature increment

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